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N. Payne, J. Feng, P. Reynolds

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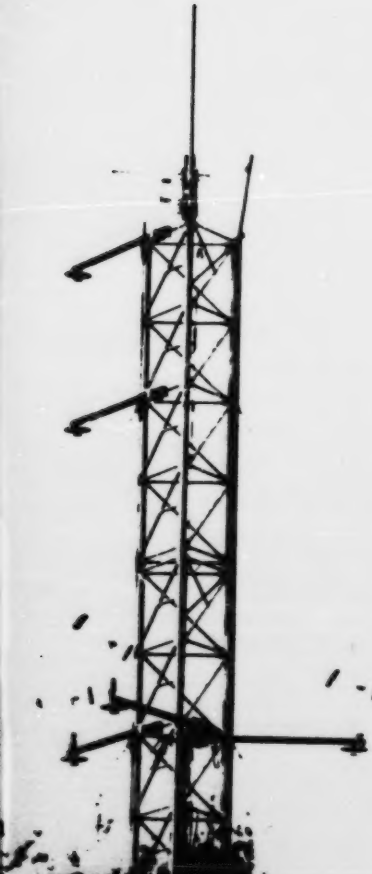

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OFF-TARGET DEPOSIT MEASUREMENTS AND BUFFER ZONES REQUIRED AROUND WATER FOR VARIOUS AERIAL APPLICATIONS OF GLYPHOSATE

FPM-X-80

N. PAYNE, J. FENG, P. REYNOLDS

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ABSTRACT

This investigation was designed to quantify off-target deposit from three types of glyphosate application for forestry use, and to estimate the width of buffer zones required around water to protect fish and their food supply from direct toxicological effects. To overcome the difficulty of estimating different buffer widths to meet the various conditions encountered, e.g., windspeed, boundary layer stability, active ingredient (a.i.) application rate, etc., a realistic worst case scenario was chosen, and data were collected accordingly. Applications of glyphosate (Roundup Monsanto) were made by helicopter using three types of dispersal system, a MICROFOIL boom (Union Carbide), a Through Valve Boom (Waldrum Specialties) and a D8-46 hydraulic nozzle. Off-target glyphosate deposits on water and foliar surfaces were measured at various downwind distances from several swaths overlaid on a crosswind track. Airborne glyphosate was also sampled. Using these measurements, mathematical equations were formulated to predict glyphosate deposits on water surfaces downwind of multiple swath applications. Based on reported measurements of the toxicity of glyphosate to salmon, rainbow trout and various aquatic invertebrates, an estimate was then made of buffer widths required around water bodies. In general, measured off-target deposit was highest from the D8-46 application, and lowest from the MICROFOIL boom application. In all applications off-target deposit on water decreased rapidly with downwind distance. A buffer width of 25 m around water bodies is adequate to protect salmon, rainbow trout and aquatic invertebrates from significant direct effects resulting from off-target deposits from two of the use strategies tested, those using the MICROFOIL and Through Valve Boom; for the third use strategy a 30 m buffer width is suggested.

RÉSUMÉ

On a voulu déterminer le dépôt hors cible résultant de trois types d'épandage de glyphosate sur les forêts et estimer la largeur des zones tampons requises autour des eaux pour protéger les poissons et leurs ressources alimentaires contre des effets toxicologiques directs. Devant la difficulté d'estimer les différentes bandes tampons requises pour les diverses conditions observées (ex.: vitesse des vents, stabilité de la couche limite, dose du principe actif, etc.), on a décidé d'appliquer un scénario réaliste de pire éventualité et de recueillir les données en fonction de ce scénario. Les épandages de glyphosate (Roundup Monsanto) ont été effectués par hélicoptère au moyen de trois types de systèmes de dispersion: une rampe MICROFOIL (Union Carbide), la Valve Boom (Waldrum Specialties) et un pulvérisateur à buse hydraulique D8-46. Les dépôts hors cible à la surface de l'eau et des feuilles ont été mesurés à diverses distances sous le vent de plusieurs bandes traitées par vent de travers. Les concentrations de glyphosate dans l'air ont également été mesurées. À l'aide des résultats obtenus, on a formulé des équations mathématiques pour la prévision des dépôts de glyphosate sur des étendues d'eau situées sous le vent des bandes traitées. En utilisant les données publiées sur la toxicité du glyphosate pour le saumon, la truite arc-en-ciel et divers invertébrés aquatiques, on a ensuite estimé la largeur des bandes tampons autour des étendues d'eau. En général, on a obtenu les plus forts dépôts hors cible avec la buse et les plus faibles avec la rampe MICROFOIL. Pour tous les épandages, le dépôt hors cible sur l'eau diminuait rapidement avec la distance sous le vent. Une bande tampon de 25 m autour des étendues d'eau serait adéquate pour la protection du saumon, de la truite arc-en-ciel et des invertébrés aquatiques contre des effets directs importants pour deux des stratégies étudiées, c'est-à-dire avec la MICROFOIL et la Valve Boom, et une bande de 30 m est suggérée dans le cas de la troisième stratégie.

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INTRODUCTION

Glyphosate (N-(phosphonomethyl) glycine) is a broad spectrum herbicide which is effective in controlling deep-rooted perennial species, and also annual and biennial broad-leaf, grass and sedge species (WSSA 1983). The isopropylamine salt of glyphosate forms the active ingredient (a.i.) of the herbicide Roundup® (Monsanto) which is registered in Canada for forestry use. The toxicity of Roundup to fish and aquatic arthropods (Folmar et al. 1979) has led the federal Department of Fisheries and Oceans and the Environmental Protection Service of Environment Canada to raise objections to the use of Roundup near water bodies because of the possibility of an overspray.

By maintaining a minimum distance of approach, or buffer zone, between a pesticide application and water body, the unwanted side-effects from a herbicide application can be reduced. The need to minimize the hazard posed by Roundup to fish and aquatic arthropods is particularly acute in the coastal region of British Columbia, where fertile alluvial sites are adjacent to important salmon-bearing rivers. The present investigation was conducted to quantify off-target deposit from aerial applications of Roundup of a type suitable for use in the mountainous B.C. terrain and to estimate the buffer width required to prevent significant mortality in populations of salmon and trout.

This investigation addresses the problem of protecting fish and aquatic species from direct toxicological effects: the problem of assessing the buffer width required to protect riparian vegetation has not been addressed. To estimate the buffer width required to protect riparian and other vegetation requires measurements of the phytotoxicity of sub-lethal glyphosate deposits, as yet unknown, but the subject of an investigation already in progress. Because of the herbicidal nature of glyphosate the buffer width required to protect vegetation may be larger than that required to protect fish and aquatic species from direct effects.

PROBLEM ANALYSIS

The use of buffer zones enable environmental impact to be controlled, however, buffer zones should not be unnecessarily wide, because this impedes efficient forest management. In this investigation buffer width estimation was based on the assumption that, where possible, worst case conditions should be used because the buffer width required to protect a sensitive area varies according to many factors. For example, the state of the atmospheric boundary layer (Pasquill 1974), structure of the plant canopy (Thom 1975), dropsize spectrum of the spray cloud and its release height (Pasquill 1974), volume and active ingredient (a.i.) application rates, and the number and spacing of the swaths laid affect buffer width. The physical and biological characteristics of the buffered water body, e.g. still or flowing water, water depth, fish species present, also affect buffer width. The use of a worst case scenario resolves the problem of defining and regulating buffer zones with many different widths. In the worst case, conditions are chosen to give the widest buffer needed to limit the unwanted toxicological effects of the herbicide to an acceptable level.

The problem of estimating a buffer width around water was split into several parts. First, measurements were made of the amount (g/m^2) of glyphosate deposited on water surfaces at various downwind distances from a single crosswind swath. Second, based on the experimental data obtained for a single swath, glyphosate deposit from a multiple swath application was calculated.

This technique has also been used by the US Environmental Protection Agency in exposure analyses (Holst 1983). Third, calculated glyphosate deposits were converted into corresponding Roundup concentrations, assuming uniform a.i. mixing in various water depths. Finally, buffer widths were estimated, using reported measurements of the toxicity of Roundup to fish and aquatic invertebrates.

Pesticide applications may require upwind, crosswind and downwind buffers. However, drops may be transported over greater distances by advection than by atmospheric diffusion or aircraft vortices (Payne et al. 1986). The largest buffer width is therefore required in the downwind direction, and this can be used for an upwind or crosswind buffer. For simplicity this investigation only addresses the problem of setting downwind buffer widths.

The dropsize spectrum of the spray cloud affects the proportion of spray that is deposited off-target during a pesticide application. In considering the effect of dropsize on the dispersal and deposition of a spray cloud, the spectrum can be viewed as comprising two dropsize ranges, large and small. These two ranges are distinguished by comparing the magnitude of the sedimentation velocities of drops with the standard deviation of vertical windspeeds in the atmospheric boundary layer. The physical significance of this classification is that small drop dispersal and deposition can be considered, to a first approximation, to be independent of sedimentation velocity and only dependent on meteorological variables e.g. atmospheric stability or windspeed, plant canopy variables e.g. canopy height, or plant density and spray application variables e.g. cloud release height, or tank mix volatility. However, for large drops the effect of the sedimentation velocity on dispersal and deposition cannot be ignored, but allows large drop behaviour to be viewed in terms of ballistics, with some spreading of the cloud about its centre of mass, caused by atmospheric diffusion (Pasquill 1974).

The magnitude of the standard deviation of vertical windspeed varies according to the state of the atmospheric boundary layer, including atmospheric stability, geostrophic windspeed, and height above ground. Typical values are 1/4-1/2 m/s, which provides a size limit of 100 to 150 μm for small drops. ULV insecticide applications generally use small drops, whereas herbicide applications generate both large and small drops (Matthews 1979). Because small drops may be transported further by the atmosphere than large drops, drift of small drops is usually of greater importance in causing environmental impact. The worst case described below applies to off-target deposit on water bodies resulting from the drift of the small dropsize range. Off-target deposit from the drift of large drops is addressed below.

Worst Case Analysis

The variables considered in choosing a worst case were those affecting the amount of a.i. deposited on water downwind of the pesticide application. For the experimental part of the study these variables fall into three categories, those related to meteorology, plant canopy, and spray application variables. For practical reasons a number of the plant canopy and spray application variables were set in accordance with operational conditions rather than the worst case.

Spray cloud dispersal experiment

The meteorological variables that affect spray cloud dispersal are atmospheric boundary layer stability, windspeed, relative humidity and air temperature. The in-

fluence of atmospheric stability lies in its effect on windspeed and turbulence, through its enhancement or damping of vertical mixing (Thom 1975). Atmospheric boundary layer stabilities are categorized as stable, unstable and neutral (Neiburger et al. 1973). Stable conditions are normally found at night and around dawn and dusk, unstable conditions are found during daylight hours when significant insolation occurs. Neutral conditions are usually found in overcast conditions or with high windspeeds, and for short periods near dawn and dusk (Sutton 1953). Stable conditions have been, and in regulatory circles still are, favoured for minimizing drift of both large and small drops. However, Crabbe and his co-workers (Crabbe et al. 1983; Crabbe and McCooeye 1985) have shown that neutral or unstable conditions minimize small drop drift, whereas stable conditions cause increased drift.

Windspeed is another important meteorological variable affecting off-target deposit. Drop deposition on a water surface occurs at a rate proportional to the drop concentration in the air above (Pasquill 1974). Increased windspeed reduces drop concentration near the ground (Crabbe and McCooeye 1985; Joyce et al. 1981; Riley 1985), this is partly because drop impaction efficiency increases with windspeed (May and Clifford 1967). The worst case for drop deposition on a water surface is, therefore, to spray in light winds, but not calm conditions.

Relative humidity (R.H.) is also influential if water-based sprays are used (Green and Lane 1964). Drop impaction efficiency increases with drop diameter (May and Clifford 1967), thus greater drift will occur with smaller dropsizes because the spray cloud will be deposited more slowly. Because R.H. is inversely related to drop evaporation rate (Rogers 1979), the worst case is to use low R.H. values in the range normally encountered while spraying. Increased air temperature increases drop evaporation rate (Green and Lane 1964; Rogers 1979), and thus reduces dropsizes and impaction efficiencies, causing increased drift. The worst case is, therefore, to use a high air temperature in the range encountered while spraying. In summary the worst case meteorological conditions for small drop drift include a stable boundary layer, light wind, low R.H. and high air temperature.

Plant canopy variables also have an effect on off-target deposit, by modifying the atmospheric boundary layer and filtering the spray cloud. The significant variables include canopy height, density (plants/m^2) and plant type, i.e. deciduous or coniferous. The effects of plant canopy variables are discussed further by Payne et al. (1986). In this investigation the canopy selected was typical of those requiring herbicide treatment, and was therefore of operational relevance, but did not provide a worst case. Small clearings were made in the canopy around each sampling station to reduce local interception of the spray cloud by the canopy and expose the collectors to ensure maximum deposition.

Spray application variables influencing dispersal include the dropsize spectrum and release height of the spray cloud, the volume and a.i. application rate, the tank mix volatility and the number and spacing of swaths. For practical reasons most of these variables were set in accordance with operational practice. Three spray applications were tested, including two designed to provide low off-target deposit and another widely used by the USDA Forest Service (L. Gross pers. comm.). Dropsize spectra are determined by the atomiser and settings, the air-speed past the atomiser and the physical characteristics of the tank mix. All of these variables were set according to the use strategies tried. Spray cloud release release height was low, in accordance with

operational practice (R. Rowe pers. comm.). However this release height also provides a worst case for spray deposited on water surfaces, because mixing and dilution of the spray cloud increases with release height, and spray deposit on water is proportional to airborne drop concentration in the lowest part of the atmospheric boundary layer (Pasquill 1974). Volume application rates ranged between 90 and 230 L/ha, as operational practice for a canopy of the height and density treated is to use high volume application rates. The tank mix diluent was water. This provides a worst case for tank mix volatility, because water has a relatively high vapour pressure compared to other diluents used in operational spray applications (Matthews 1979; Riddick and Bunger 1970). A high volatility tank mix causes fast drop evaporation, which in turn decreases dropsize and impaction efficiency, resulting in greater drift. Swath width was also set in accordance with operational practice.

Modelling glyphosate deposit from multiple swath applications

To estimate the widths of buffer zones required around water bodies to protect fish and aquatic invertebrates during operational Roundup applications, it is necessary to know how much a.i. is deposited on the water surfaces and its biological effect. Because a.i. deposit and biological effect diminishes with distance from the spray application, at a certain distance from the application the environmental impact is negligible, i.e., comparable with natural influences. A buffer can be estimated from this distance. This approach to buffer estimating was devised and first used in estimating buffers required during applications of the insecticide permethrin (Payne et al. 1986).

A worst case was also chosen for modelling deposit from multiple swath applications. Off-target deposit downwind of a multiple swath application increases with the total amount of a.i. sprayed, which in turn depends on the a.i. application rate and the size of treatment area. The a.i. application rate was 2.1 kg acid equivalent (a.e.)/ha, the maximum recommended rate. The swath number was also worst case, based on a 100 ha (1 x 1 km) area, which is at or near the upper limit for size of treatment area (A. Robinson pers. comm.). Swath lengths were sufficient to make the application representative of an infinite line source at the downwind distances where deposits were sampled (Payne 1983), and thus provide worst case deposits.

MATERIALS AND METHODS

Site and Canopy

The experiment was conducted on a nearly flat area in the Skeena River Floodplain, near grid reference 129°23'W, 54°19'N (Fig. 1). With the wind direction chosen for the spray trials, i.e. up-valley and approximately SW, there was an upwind fetch of nearly flat terrain about 1 km long, bearing a largely deciduous forest with canopy height in the 10-30 m range. Upwind of this was a fetch of about 3 km comprising wooded floodplain and open water. Over this distance the valley floor was at least 2.5 km wide. Wind directions suitable for the trials were restricted to up and down the valley because of the lee eddies caused by air flow over mountains (Atkinson 1981; Scorer 1978), which results in irregular spray cloud dispersal.

The spray site was a 1968-69 cutover, which bore a largely deciduous canopy with species composition and tree heights as given in Table 1. Canopy composition and tree heights were measured at five locations, 100 m apart along a transect across the site. At each location all trees within a circular area with radius 10 m were counted, and the heights of ten randomly selected trees were measured. The site was covered with red alder, with dense willow thickets near the narrow side channels which crossed the site at two points.

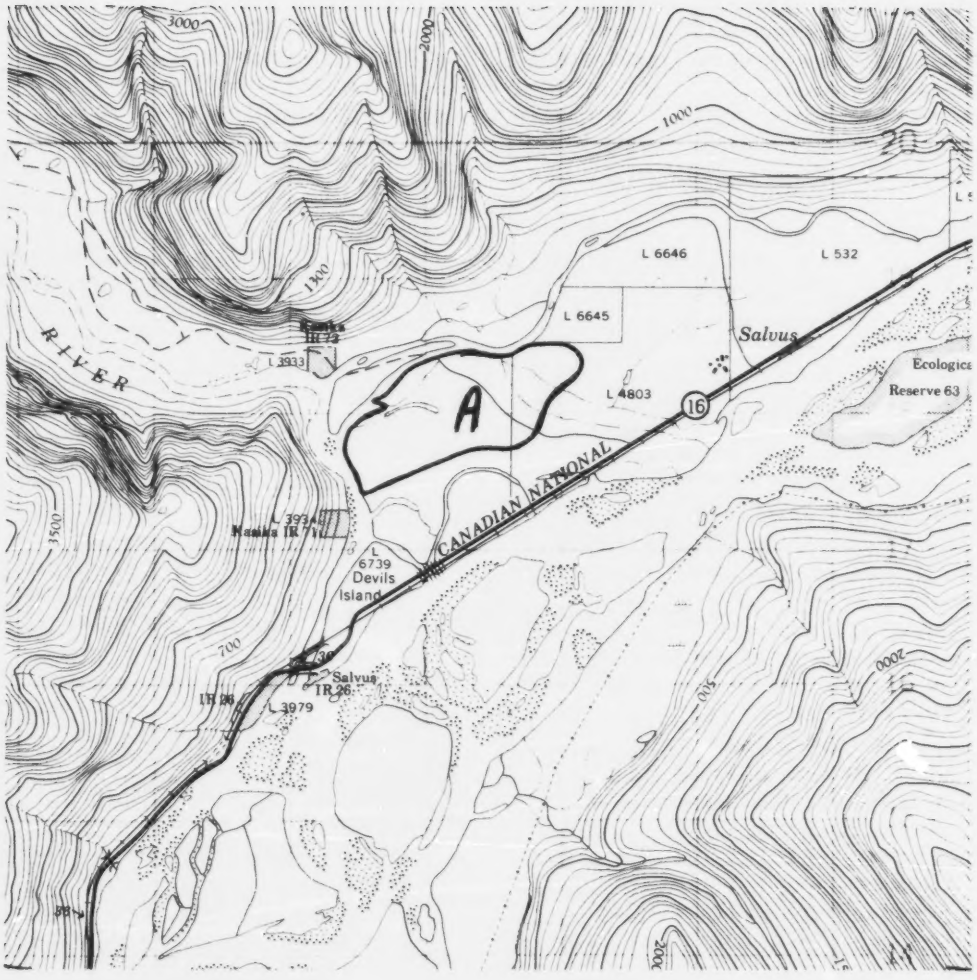

Figure 1. Portion of topographic map (1:50,000, 103-I/6, Salvus, 1 km grid), showing location of experimental site (A) in Skeena river valley.

Meteorological measurements

On-site meteorological measurements were used to select suitable spraying conditions and to characterize conditions during the spray application and dispersal. Windspeed was measured at 13 and 22 m above ground level (agl), with cup anemometers (threshold speed 0.34 m/s, Heathkit digital weather computer Model ID-4001, Heath Co., Benton Harbour, MI). At 13 m agl the lower anemometer was just above the canopy. Apparent windspeed was corrected to estimate true windspeed using calibration curves measured on a whirling arm calibration rig designed and built at FPMI. Wind direction was measured at 22 m agl (wind vane, Heathkit digital weather computer). Air tempera-

Table 1. Plant canopy composition on spray site

Species	Plant density (Avg stems/ha)	Plant height (m) (Avg/SD)
Red Alder *(Alnus rubra* Bong)	1318	17.3/4.3
Black Cottonwood *(Populus trichocarpa* Torr. & Gray)	146	27.3/2.1
Bebb's willow Sarg. *(Salix bebbiana)*	1236	9.7/2.2

tures were measured at 13 and 22 m agl with diode type sensors (Heathkit digital weather computer ID-4001), shaded to prevent radiative heating. Relative humidity was measured at 2 m agl (capacitance type hygrometer, Heath Co.) during the spray application and dispersal. Meteorological measurements were manually recorded at half minute intervals during the spray application and dispersal, a period of 20-30 minutes depending on the windspeed.

Spray applications

Trials were conducted using three different use strategies. A helicopter was chosen for all applications because of its manouverability, and hence its suitability for applying pesticide in mountainous terrain. Different dispersal systems were used in each trial, but spray cloud release heights, and meteorological conditions were similar in all trials.

The application in trial #1 was made with a MICROFOIL boom. The active ingredient (a.i) and volume application rates were 3.4 kg a.e./ha and 230 L/ha per swath respectively. The a.i. application rate was chosen to provide detectable residues at the sampling stations furthest downwind, however the results presented below are for the maximum recommended rate of 2.1 kg a.e./ha. The volume application rate is representative of herbicide applications in which a dense multi-storey plant canopy is treated. Spray drift from the MICROFOIL boom atomiser is relatively low with the configuration used (Yates et al. 1978); however, the volume application rate is high and consequently the work rate is low. The MICROFOIL boom within the manufacturer's recommended operating range for minimum drift (MICROFOIL boom user manual). The tank mix sprayed was a 4.2% v/v mixture of Roundup and water, i.e. 1.5% w/w solution of the isopropylamine salt of glyphosate. From a previous study (van Vliet et al. 1986) using a nozzle, nozzle orientation, boom pressure, crosswind and tank mix similar to this application, the dropsize spectrum in trial #1 was assumed to have volume and number median diameters of about 3000 and 2700 microns respectively at release. Van Vliet et al. (1986) found that about 4% of drops had diameters less than 1600 microns, representing about 0.63% of the spray volume at release.

Swath-length and number were an important consideration in the design of the spray trials. Measurements of average spray deposit from a single swath were required for modelling. In each trial several swaths were overlaid along a crosswind track to reduce deposit variability and provide sufficient a.i. for detection at the sampling stations furthest downwind. Each swath was long enough to satisfy the infinite line condition. In trial #1 three swaths 300 m in length were applied.

The application in trial #2 was made with a Thr Valve Boom (TVB). A.i. and volume application rates were 2.2 kg a.e./ha and 91 L/ha per swath respectively. The TVB is a new dispersal system, introduced in 1983 and reported to provide good drift control (manufacturer's tests). As used in trial #2 the TVB provides lower volume application rates and consequently higher work rates than the MICROFOIL boom configuration employed in trial #1. The TVB was 9.14 m in length and fitted with 62 0.045 in. burr nozzles (1.14 mm I.D.) and 2.03 mm control orifices, with nozzles evenly spaced along the boom and pointed backwards to reduce relative fluid velocity; each nozzle comprised 15 jets. The TVB was forward-mounted on a Bell 47-T helicopter and flown at about 20.1 m/s at approximately 3m above the canopy height. Boom pressure was 171.75 kPa, and total flow rate was about 165 L/min. Planned swath width was 15 m. The tank mix sprayed was a 6.7% v/v mixture of Roundup and water, i.e. 2.4% w/w solution of the isopropylamine salt of glyphosate. From a previous study (van Vliet et al. 1986) using a nozzle, nozzle orientation, boom pressure, crosswind and tank mix similar to those used in this application, the dropsize spectrum in trial #2 was assumed to have volume and number median diameters of about 1000 and 150 microns respectively at release. Van Vliet et al. (1986) found that about 30% of drops had diameters less than 100 microns, representing 0.04% of the spray volume at release. In trial #2 five swaths 300 m long were applied.

The application in trial #3 was made with a D8-46 hydraulic nozzle. A.i. and volume application rates were 2.1 kg a.e./ha and 90 L/ha per swath respectively. This use strategy is often used in USDA-Forest Service herbicide applications (L. Gross pers. comm.). The boom was 8.53 m long and carried 32 hollow cone nozzles (disc number 8, 46 whirlplate). Nozzles were evenly spaced along the boom and pointed backwards to reduce relative fluid velocity. The dispersal system was mid-mounted on a Bell 47-T helicopter and flown at about 20.1 m/s at approximately 3 m above canopy height. Boom pressure was about 171.75 kPa, and the total flow rate was 163 L/min. The planned swath width was 15 m. The tank mix sprayed was a 6.5% v/v mixture of Roundup and water, i.e. 2.3% w/w solution of the isopropylamine salt of glyphosate. From a previous study (Yates et al. 1985) using a nozzle, nozzle orientation, boom pressure, crosswind and tank mix similar to those used in this application, the dropsize spectrum was assumed to have volume and number median diameters of about 460 and 70 microns respectively at release. Yates et al. (1985) found that about 60% of drops had diameters less than 100 microns, representing about 1% of the spray volume at release. In trial #3 four swaths 300 m long were applied.

The boom length should be less than the rotor diameter to reduce the effect of the helicopter vortices on spray cloud dispersal and swath width (Quantick 1985). In trials #1, 2 and 3 the boom lengths were about 69, 79 and 74% of the rotor diameter (11.5 m).

Off-target Deposit Measurements

Sampling methods

The layout of the experimental site is shown in Figure 2; swaths were laid along a NW-SE crosswind track (B). Sampling stations (C) were set up at distances of 25, 50, 75, 100 and 200 m, measured along the perpendicular bisector (NE-SW) of the cross-

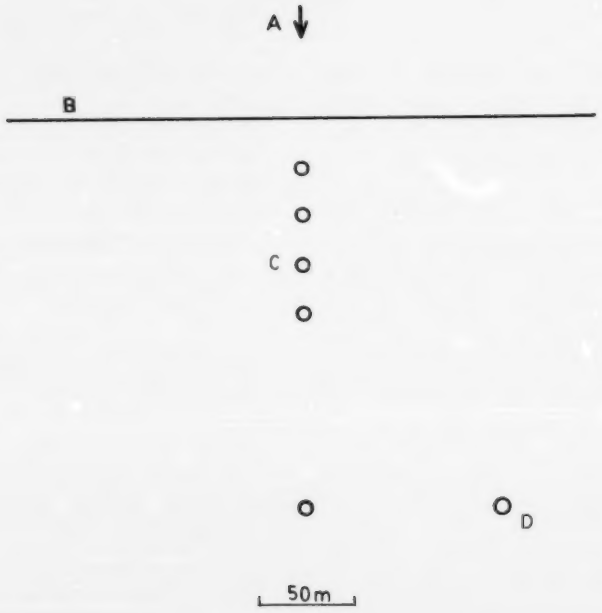

Figure 2. Layout (to scale) of spray cloud dispersal experiment, with planned wind direction (A), 300 m crosswind track (B), sampling stations (C) and meteorological station (D).

wind track. Glyphosate deposit on water and foliar surfaces and glyphosate area dose were measured. Average wind directions during the applications were within 20 degrees of the planned direction (A) -SW, and downwind distances of the stations from the swaths were therefore within 6% of the planned values. Consequently no corrections were made to downwind distances. Circular clearings 8 m in diameter (50% canopy height) were made around each sampling station to reduce the interception of the spray cloud by the canopy.

Glyphosate deposit on water surfaces was sampled at all stations with collectors comprised of a polyethylene sampling sheet with dimensions 0.3 x 1 m pegged over a larger polyethylene sheet (2 x 2 m), pegged over a similar area cleared of vegetation. These collectors were aerodynamically similar to a water surface and thus airflow over collectors was similar to that over a water surface. Spray deposits on a water surface and the collector were therefore assumed to be similar. At the three closest stations one sheet was exposed; at the 100 and 200 m stations the sampling area was doubled. To prevent contamination in the second and third trials a backing sheet was placed beneath the sampling sheet. Glyphosate deposits on the sampling sheet were quantified.

Foliar deposits at the 50, 100 and 200 m stations were sampled with collectors comprised of a red alder branch on which the upper and lower surfaces of ten randomly chosen leaves were covered with a polyethylene sheet, cut to match the leaf shape. Red alder was chosen as a common weed species in B.C. herbicide applications: an apical branch was held vertically at the canopy top, and a dorsal branch held horizontally at about 2m agl. These branches were supported on light weight masts designed for use in forest canopies (Beveridge and Payne 1986). Glyphosate deposits on the polyeth-

ylene leaf covers were quantified. The areas of polyethylene leaf covers were measured with a polar planimeter (Davis and Kelly 1967).

Glyphosate area dose is the total amount of a.i. passing through 1 m^2 of crosswind area (Davies 1966). It provides an indication of the amount of a.i. that could be respired by humans and animals. Because glyphosate has a very low vapour pressure (WSSA 1983), airborne a.i. is largely contained within spray drops and unnecessary. Measurements of glyphosate area dose (gad) were made at the 50, 100 and 200 m sampling stations using Rotorod samplers (Ted Brown Associates, 26338 Esperanza Drive, Los Altos Hills, CA 94022), which collect drops by inertial impaction (Fig. 3). Based on measurements of impaction efficiency (May and Clifford 1967), these devices were assumed to collect all drops in the volume of air sampled, and the glyphosate deposit (g/m^2) on the collecting sur-

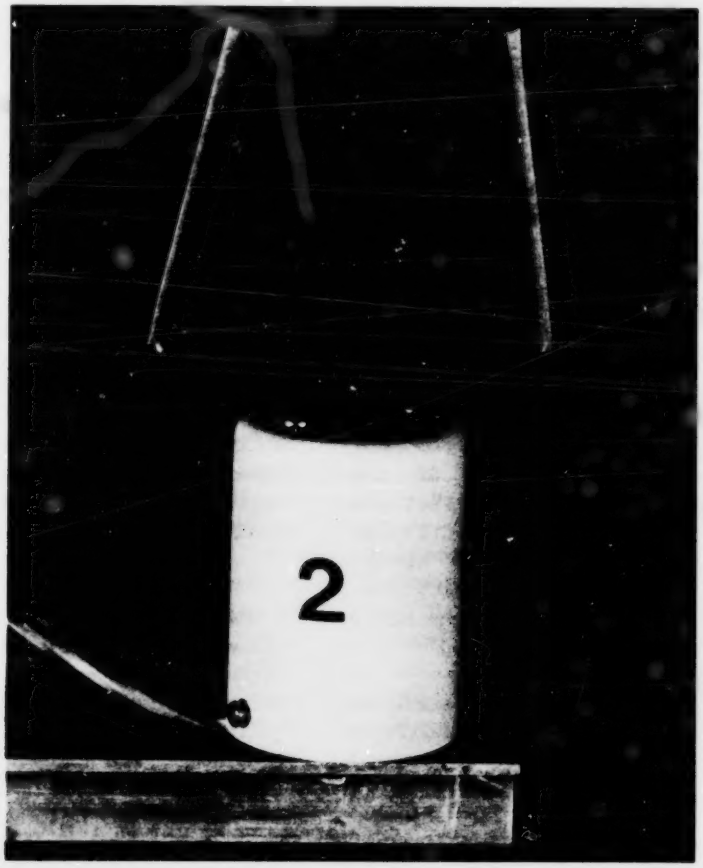

Figure 3. Rotorod sampler with 'u' rod and teflon collectors.

face is therefore proportional to gad. Drops were collected on two 2.6 mm O.D. teflon cylinders mounted on 'U' rods, a sampling configuration developed by FPMI. Two samplers were deployed at each station supported on the lightweight masts, with one at canopy top, and the other at about 2 m agl. Glyphosate deposits on the teflon cylinders were quantified.

Measurements of glyphosate deposit on leaf covers and rotorod collecting surfaces at canopy top and at 2 m were averaged to give the values reported. Glyphosate deposits on foliar covers on the upper and lower leaf surfaces were also averaged.

All collectors were exposed for up to 30 minutes after the spray application was completed to allow the spray cloud to be advected over all sampling stations, and for drops to penetrate the plant canopy and be deposited. Samples were then collected and stored at about -10°C, until deposits were quantified by high performance liquid chromatography (HPLC).

Glyphosate quantification

Spray deposits were washed from collecting surfaces with 0.1N hydrochloric acid by sonication and then mechanical agitation. The rinsings from the ground sheets were cleaned-up with anion- and cation-exchange columns, according to the method described by Cowell et al. (1986). Samples were then filtered (0.45 micron pore, Millipore SLHV 025 NS filter) and the residues of glyphosate and its principal metabolite aminomethyl-phosphonic acid (AMPA) were quantified by HPLC. Detection and derivatisation were carried out using a methodology developed by Monsanto (1983, unpublished report). The chromatograph was fitted with a variable wavelength UV/vis light detector and a ninhydrin postcolumn reactor. Glyphosate and AMPA residues were quantified by measuring peak heights of detector response, which were then interpreted by comparison with analytical standards, injected after every second sample. With this method the limit of quantification for glyphosate was about 500 ng, while that for AMPA was about 150 ng. AMPA comprised less than 6% of the glyphosate residue in any sample.

Estimating Buffer Width Required Around Bodies of Water

The total a.i. deposited on water bodies downwind from a multiple swath application was calculated with a computer program by adding up the contributions from individual swaths. The deposit-distance relationships used in the program were based on the experimental measurements of glyphosate deposit from a single swath with a.i. application rate of 2.1 kg/ha, with interpolation between data points. This interpolation was made by assuming that glyphosate deposit on water surfaces varied according to the equation:

$$J = A.x^B \qquad \text{Equation 1}$$

where J is glyphosate deposit ($\mu g/m^2$), x is downwind distance from swath and A and B are constants. This is the usual mathematical equation used to describe deposit-distance relationships beyond the distance of maximum deposit (Pasquill 1974; Sutton 1953).

The mathematical model used to calculate off-target deposit was based on measurements of deposit from a single swath, and required an extrapolation from a downwind distance of 200 m to about 1 km. The curve fitted to the off-target deposit measurements was extrapolated beyond 200 m downwind using the curve interpolated between the measurements at 100 and 200 m downwind. This extrapolation gives an overestimate of spray deposit for two reasons. First, the spray lines are subject

to crosswind spreading by atmospheric diffusion. This lateral broadening will dilute the cloud and reduce airborne drop concentrations and hence spray deposit. Second, the cloud is winnowed as it moves downwind because the efficiency of inertial impaction increases with dropsize. Thus large drops are deposited faster than small drops. As a result the average deposition velocity of the cloud is reduced and spray deposit is reduced from the extrapolated value. This overestimation of spray deposit is consistent with the worst case approach used in the investigation.

Buffer widths were estimated as follows. Using the model, glyphosate deposit was calculated at various downwind distances from a 1 x 1 km spray application. The predicted glyphosate deposit was then converted to a glyphosate concentration in water, by assuming complete and even mixing in various water depths, with no further dilution. This assumption is worst case because glyphosate is rapidly adsorbed onto suspended particulate matter which reduces its availability to aquatic organisms (Tooby 1985), and the salmon and trout populations requiring protection are in flowing water, which causes dilution. Buffer widths were estimated from the downwind distance at which the predicted glyphosate concentration fell below an acceptable level, as determined from published measurements of glyphosate toxicity to fish and aquatic invertebrates.

RESULTS AND DISCUSSION

Meteorological Measurements

Meteorological conditions during the trials (Table 2) provided the worst case conditions required to maximize glyphosate deposit on water.

Off-target Deposit Measurements

Figures 4 (a) and 4 (b) show measurements of glyphosate deposit (g/m^2) on ground sheets and leaf covers respectively, at various downwind distances from a single crosswind swath with an a.i. application rate of 2.1 kg a.e./ha. Actual measurements were adjusted to correspond to this rate. The measurements represent the average deposit from a single swath. Table 3 presents adjusted measurements of glyphosate deposit (g/m^2) on Rotorod collecting surfaces at various downwind distances from a similar application. The ratio of foliar glyphosate deposit at canopy top, to that at 2 m was 1.24 (S.D.=1.00, n=9), based on an average over all sampling stations and all trials. This ratio indicates that average foliar deposit from the spray cloud increased slowly with height above ground.

It is apparent from Figures 4 (a) and (b) and Table 3 that off-target glyphosate deposits and glyphosate area doses were in general lowest for the MICROFOIL application and highest for the D8-46 hydraulic nozzle. These measurements are consistent with the estimated dropsize spectra presented above, which indicate the spray volume in drops with diameters less than 100 m was greatest in the D8-46 application, and least in the MICROFOIL application.

Glyphosate deposits on ground sheets in trial #1 (MICROFOIL) were lower by a factor of 10 to 100 than in trials #2 (TVB) and #3 (D8-46), at distances of 75 m and less from the track. However, by 200 m downwind the glyphosate deposits on ground sheets in trials #1 and #2 were similar and approximately half the amount found in trial #3. Glyphosate deposits on leaf covers 50 m downwind of the MICROFOIL application (trial #1) were 10 to 50 fold lower than that measured from the other two applications.

Table 2. Meteorological measurements during spray applications and dispersal (avg./SD)

Trial number	1	2	3
Date of trial	19/9/84	30/9/84	30/9/84
Time spraying commenced	19:15	16:30	19:20
Sunset (Pacific standard time)	20:46	20:22	20:22
Cloud cover (eighths)	0-1	5-6	8
Windspeed @ 13m agl (m/s)	0.4/-	0.5/0.2	0.4/0.1
Windspeed @ 22m agl (m/s)	0.8/0.3	0.9/0.3	0.6/0.3
Air temperature @ canopy top, 13m agl (°C)	8	15	11
Air temperature @ 22m agl (°C)	10	16	12
Relative humidity (%)	80	76	88
Stability of lowest 20m of atmosphere	Stable	Stable	Stable

Table 3. Measurements of glyphosate deposit ($\mu g/m^2$) on Roto-rod collecting surfaces at various downwind distances from a single crosswind swath with a.i. application rate of 2.1 kg a.e./ha

Downwind distance (m)	Deposit on Rotorod collecting surfaces ($\mu g/m^2$)		
	MICROFOIL	TVB	D8-46
50	380	1960	13400
100	103	195	536
200	130	<71	<71

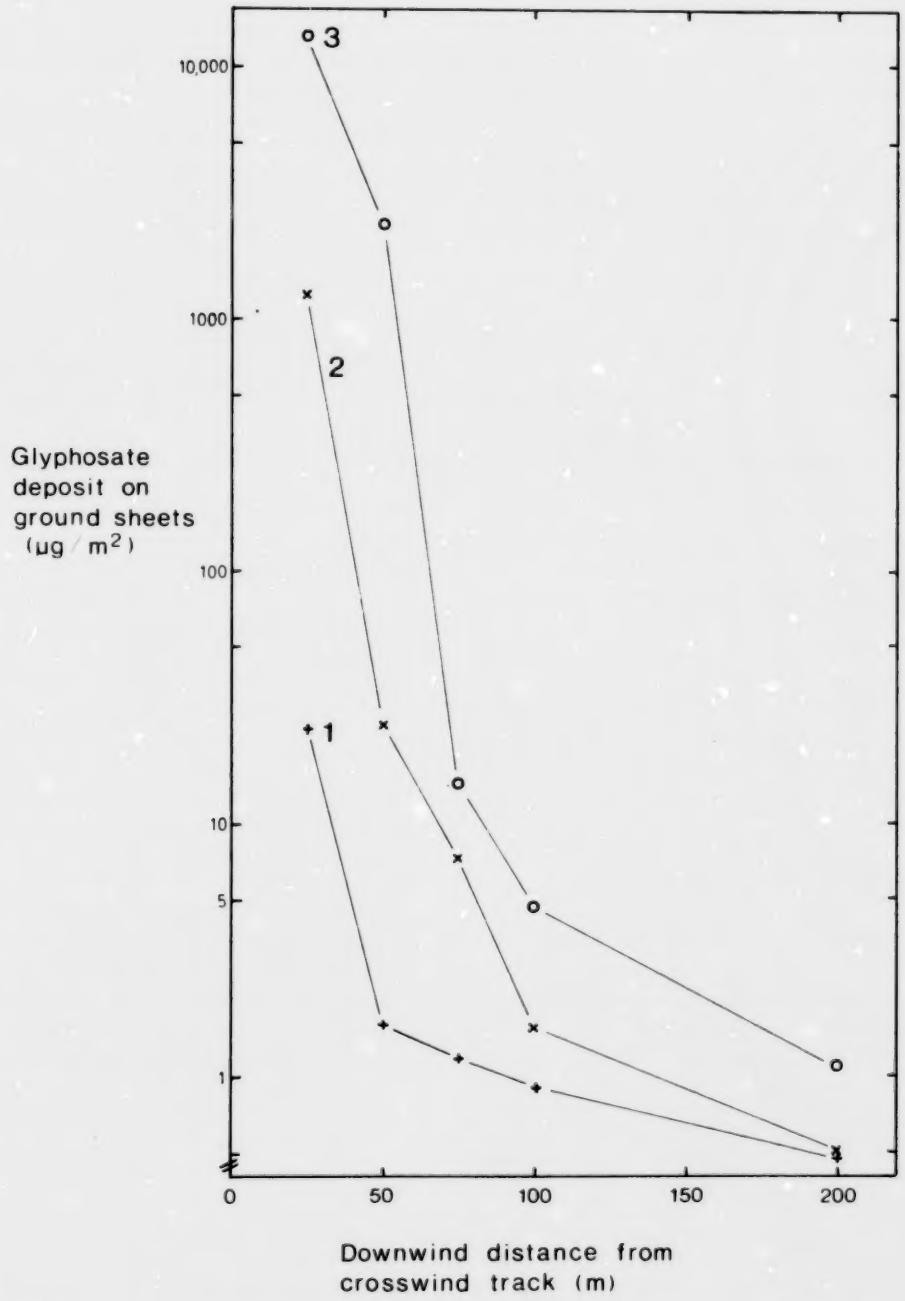

Figure 4. (a). Glyphosate deposit on ground sheets downwind of a single aerially applied swath, with a.i. application rate of 2.1 kg a.e./ha. Labels 1, 2 and 3 denote trial numbers.

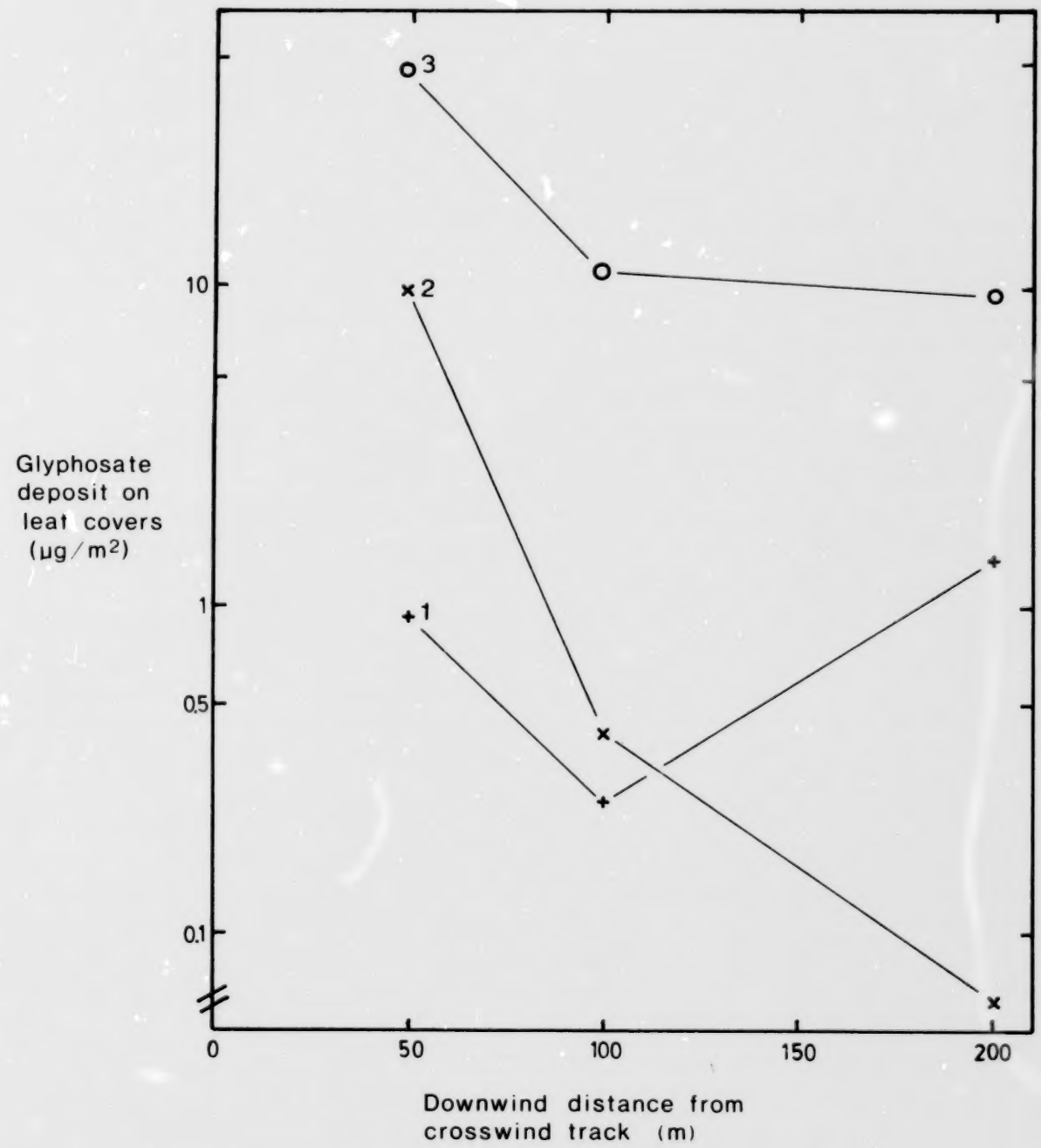

Figure 4. (b). Glyphosate deposit on leaf covers downwind of a single aerially applied swath, with a.i. application rate of 2.1 kg a.e./ha. Labels 1, 2 and 3 denote trial numbers.

In contrast to the glyphosate deposits on ground sheets, large differences in foliar glyphosate deposit were found at 200 m downwind. The foliar deposit at 200 m in trial #1 (MICROFOIL) is anomalously large. Glyphosate residues collected by Rotorods at 50 m downwind in trial #1 were lower than those in trials #2 (TVB) and #3 (D8-46) by factors of about 5 and 35 respectively. In trials #2 and #3 glyphosate collected by Rotorods 200 m downwind from the swath was undetectable (residue was less than 200 ng). Measured Rotorod deposit at 200 m in trial #1 is anomalous. In trials #1 and #2, glyphosate deposits on ground sheets were higher than those of leaf covers, but this was not the case in trial #3.

Off-target Deposit From Multiple Swath Applications

Glyphosate deposits on water surfaces downwind of multiple swath Roundup applications at 2.1 kg a.e.,/ha were calculated using the model described above. The model predictions are presented in Figure 5. A 13 metre swath width was used for the MICROFOIL application and a 15 m swath width for the TVB and D8-46 applications. For the MICROFOIL results extrapolation downwind of the 200 m data point was made using the interpolation equation between the 100 m and 200 m data points. For the TVB and D8-46 results extrapolation beyond 200 m was made using the exponent (B) obtained from the MICROFOIL extrapolation. The exponents derived for the TVB and D8-46 from Fig. 4(a) would have given quicker attenuation of deposit than the exponent calculated for the MICROFOIL. In view of the proportions of spray volume in drops with diameters less than 100 m, this was thought to be an unrealistic assumption. No extrapolation was made upwind of the 25 m sampling station because of swath displacement (see below). Table 4 shows downwind distances from the closest swath at which calculated glyphosate deposit on water surfaces falls to 0.1, 1, or 5% of the a.i. application rate, i.e. 210, 2100 and 10,500 g/m^2.

Table 4. Distances from final downwind swath at which glyphosate deposit on ground sheets reaches 5, 1 and 0.1% of a.i. application rate of 2.1 kg a.e./ha

Glyphosate deposit as percentage of 2.1 kg/ha (%)	Downwind distance from final swath (m)		
	Microfoil	TVB	D8-46
5	< 25	< 25	28
1	< 25	< 25	49
0.1	< 25	35	62

Biological Effect of Glyphosate in Water Bodies

The biological effect of calculated glyphosate deposits on water resulting from a 1 x 1 km Roundup application (Fig. 5) was assessed using toxicological data from several studies.

Roundup toxicity to fish has been measured by EVS Consultants in static tests for Monsanto (1986a-d), using coho and chinook salmon smolt *(Oncorhynchus kisutch & O. tshawytscha)* and rainbow trout fry *(Salmo gairdneri)*. The tests showed that following a 10 d exposure to Roundup in freshwater concentrations up to 3.2 mg

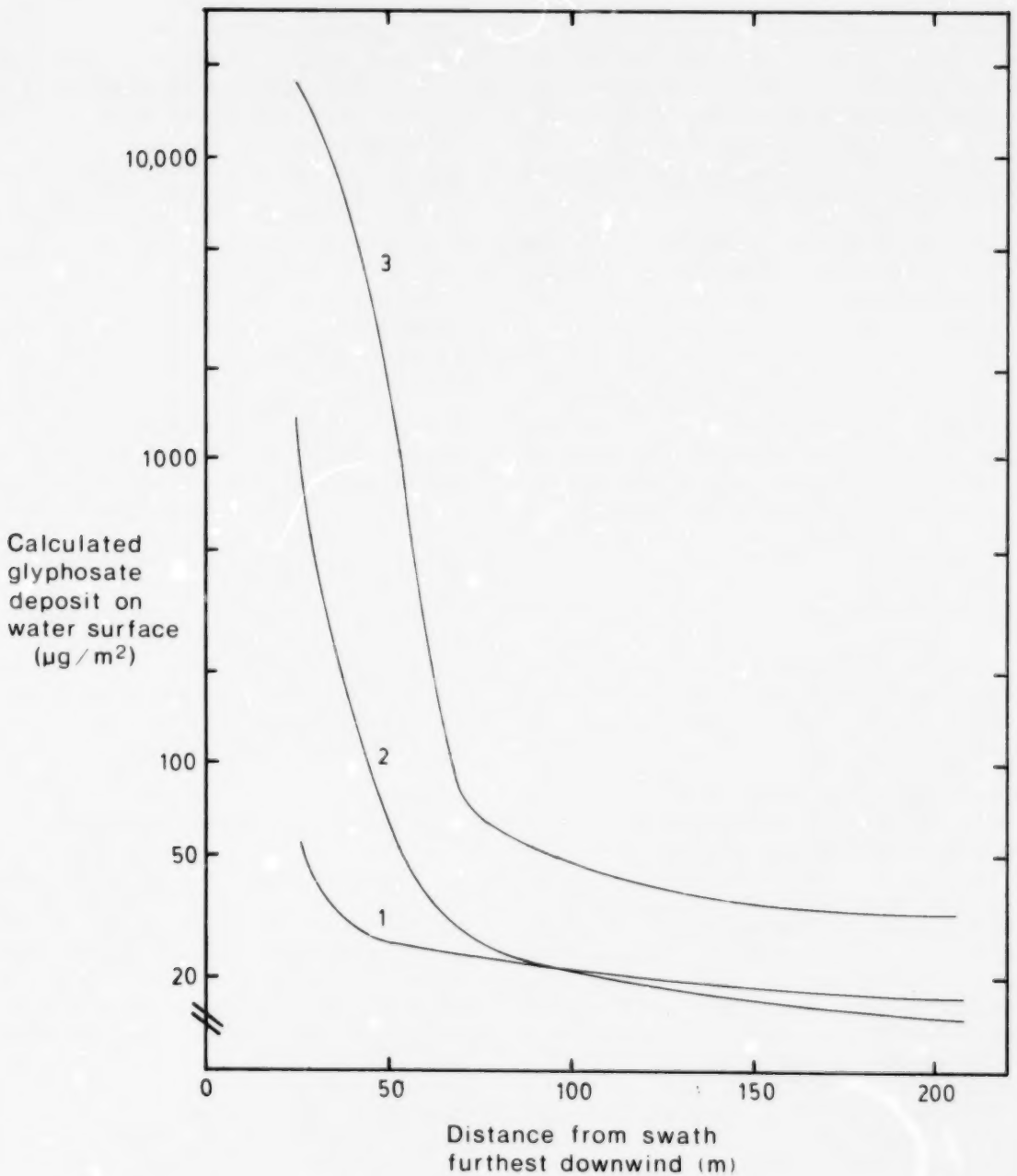

Figure 5. Calculated glyphosate deposit on water surface downwind of 100 ha (1 km x 1 km) multiple swath application at 2.1 kg a.e./ha. Labels 1, 2 and 3 denote trial numbers.

Roundup/L, coho salmon smolts were capable of survival and adapting to seawater. Static tests gave measured 96h LC 50s of 22.4, 20 and 26 mg Roundup/L respectively for coho and chinook salmon and rainbow trout. Fish mortalities of less than 10% were reported for concentrations up to 6.6 mg Roundup/L.

Hildebrand et al. (1982) studied the effects of Roundup on fingerling rainbow trout populations, and reported 96 h LC 50s of 52 and 54.8 mg Roundup/L respectively from field and laboratory bioassays. Roundup was also applied manually to shallow forest streams in which pens containing fingerling rainbow trout (2.3 g) had been placed in water depths between 15 and 29 cm. A.i. application rates of 2.2, 22 and 220 kg a.e./ha were used in direct oversprays. No rainbow trout mortality occurred and no symptoms of stress or physical discomfort were observed. Glyphosate concentrations in water were not reported.

A study by Folmar et al. (1979) reported acute Roundup toxicities from static tests on various fish and aquatic invertebrates. The 96 h LC 50s for adult rainbow trout and fathead minnow *(Pimephales promelas)* were 8.3 and 23 mg Roundup/L respectively. The rainbow trout life stage most sensitive to Roundup was the fingerling (1.0 g), having a 96 h LC 50 of 1.3 mg Roundup/L. No changes in fecundity were observed in adult rainbow trout exposed for 12 h to 2.0 mg Roundup/L. The 48 h EC 50s (immobilising concentration) measured for first-instar daphnids *(Daphnia magna)* and fourth-instar midge larvae *(Chironomus plumosus)* were 3.0 and 18 mg Roundup/L respectively.

Hildebrand et al. (1980) also studied the effect of Roundup on daphnid *(D. magna)* populations. This abundant aquatic invertebrate forms a significant part of the diet of fish (Crosby and Tucker 1966). A manual application of Roundup was made to forest ponds containing pens into which adult *D. magna* had been placed. The pens restricted the organisms to a surface layer 30cm in depth. A.i. application rates of 2.2, 22 and 220 kg a.e./ha were used in a direct overspray. Survival rates exceeded 90% in all trials, and the control survival rate was similar to that obtained at 220 kg a.e./ha. Glyphosate concentrations in water were not reported.

Based on the EVS laboratory study cited above, 1.0 mg Roundup/L, equivalent to about 0.3 mg glyphosate a.e./L, will limit mortality to less than 10% in populations of salmon smolt and rainbow trout fry. In addition the study by Hildebrand et al. (1982) showed no rainbow trout mortality with theoretical Roundup concentrations from oversprays of 249-480 mg/L. In contrast the laboratory study by Folmar et al. (1979) indicates that Roundup concentrations of 1.0 mg/L, if maintained for 96 h, could result in about 50% mortality in the most sensitive life stage of rainbow trout. The field study by Hildebrand et al. (1980) indicated greater than 90% survival of adult *D. magna* at theoretical Roundup concentrations of 250 mg/L, resulting from oversprays.

Buffer Width Estimates

Table 5 shows the predicted Roundup concentrations (µg/L) in water bodies at various downwind distances from 100 ha Roundup applications with the three use strategies tested. The buffer widths required around water to limit Roundup concentrations to 1 mg/L were estimated for water depths of 0.1, 0.25 and 0.5 m. For each combination of use strategy and water depth, the downwind distances from the final swath at which Roundup concentrations fall to 1 mg/L are less than 25m. A buffer width of 25 m is therefore adequate to limit off-target deposit from small drop drift to the chosen level for all three use strategies

tried. Extrapolation of the spray deposit data to distances less than 25m in order to estimate a more exact buffer width is inadvisable because of swath displacement, a discussion of which follows.

The model and data from this investigation can be used to estimate buffer widths for spray applications similar to those tested, but with different a.i. application rates and areas. However, the data from this investigation are not directly applicable for other use strategies, e.g. using different dispersal systems, emission rates or airspeeds, due to differences in dropsize spectra. When measurements of the phytotoxicity of sub-lethal glyphosate deposits become available, the off target deposit measurements from this investigation can be used to estimate buffer widths required to protect riparian and other vegetation.

Swath Displacement

Swath displacement or 'large' drop drift was estimated for the three use strategies tried in this investigation, for worst case meteorological conditions for 'small' and 'large' drop drift. Drop flight times are shorter for large drops than for small, because sedimentation velocity increases with dropsize. In the present trials large drop flight times were typically 1-10s. Drop evaporation during flight was slight, because drop lifetimes are much larger than flight times, e.g. a 200 m diameter water drop has a lifetime of about 200s in air at 20°C with a relative humidity of 80% (Matthews 1979). Windspeed is the most influential meteorological variable causing large drop drift, with higher windspeeds causing greater swath displacement. Atmospheric stability also affects swath displacement through its effect on the horizontal wind profile. However for the low release heights in these trials differences caused by stability are small and were ignored in estimating swath displacement.

Swath displacement was estimated using ballistics (Pasquill 1974). The following assumptions were made. The large drop component of the spray cloud was represented by

Table 5. Predicted Roundup concentrations (µg/L) in water bodies at various downwind distances from 100 ha Roundup applications at 2.1 kg a.e./ha

Downwind distance (m)	Trial #1			Trial #2			Trial #3		
	Water depth (m)								
	0.1	0.25	0.5	0.1	0.25	0.5	0.1	0.25	0.5
25	1.77	0.72	0.36	46	18	9.2	590	240	120
50	0.85	0.33	0.17	2.0	0.82	0.39	82	32	16
75	0.79	0.31	0.15	0.99	0.39	0.20	2.2	0.89	0.46

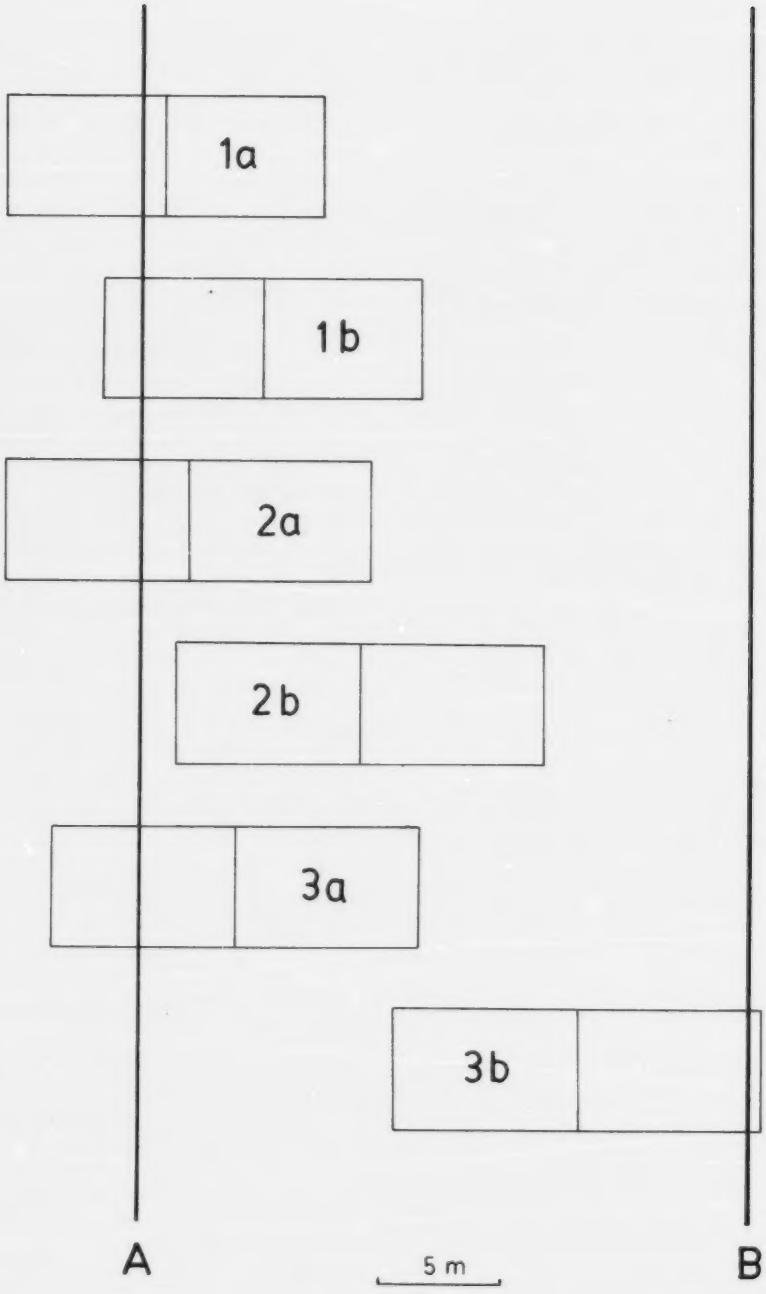

Figure 6. Position of large drop deposit in relation to crosswind release line (A) and line 25 m downwind (B) (to scale). Labels 1, 2 and 3 denote trial numbers, suffixes a and b refer to windspeeds of 1 and 4 m/s.

the volume median dropsize, and the sedimentation velocity was chosen accordingly. The spray cloud was assumed to be advected through the 3m release height (above canopy), and the top third of the canopy height (1/3 x 18m = 6m). Windspeed inside a forest canopy increases with height, however in the lower two thirds of the canopy windspeeds are low (Oliver 1971, 1975), and advection is slight. The average horizontal windspeed at canopy top was used for calculating displacement. In fact, the average horizontal windspeeds above and below this height are greater and smaller respectively than the value at canopy top, making this approximation a reasonable one. The effect of the two counter rotating aircraft vortices on swath displacement was assumed to be small, with the vortices acting to spread the cloud about its centre of mass rather than causing advection of the total cloud. Swaths were crosswind.

In the MICROFOIL application the volume median diameter (VMD) was about 3000 m. A water drop of this size has a sedimentation velocity of about 8.1m/s (Rogers 1979). In the TVB and D8-46 applications the VMDs were assumed to be about 1000 and 460 µm. The sedimentation velocities of water drops with these diameters are about 3.9 and 1.9 m/s (Hinds 1982).

At the windspeeds used for the present trials, about 1 m/s at canopy top, the swath displacements i.e. the distance from the centre of the spray deposition pattern to the release line for MICROFOIL, TVB and D8-46 were estimated to be about 1, 2 and 4m respectively. Under worst case conditions for large drop drift, with an average horizontal windspeed of 4 m/s (about 16 km/h), swath displacements were estimated to be about 5, 9 and 18m respectively. It should be noted that these swath displacements refer to the large drop component of the spray cloud, and predict the average displacement. Some large drops will travel further, others less far.

The value of this estimate of swath displacement is that it allows small and large drop drift to be compared. Figure 6 shows estimated swath position in relation to the release line for the three types of application used, in average horizontal windspeeds of 1 and 4 m/s. Swath widths were those described above. Using measurements of small drop drift, a buffer of 25m from the furthest downwind swath has been shown to protect fish and aquatic invertebrates from significant direct toxicological effects of glyphosate. However, if large drop drift is taken into account, it is apparent that for the D8-46 a larger buffer may be required to prevent the swath from reaching the water body by displacement.

Effect of Roundup Overspray

A calculation was made of the a.i. concentration in water resulting from a Roundup overspray. To provide worst case deposit all a.i. was assumed to be deposited in the swath region. For a spray over still water 0.1 m deep, assuming complete and even mixing, and no further dilution, the resulting glyphosate (a.e.) concentration is 2.1 mg/L. In flowing water dilution will occur, reducing the concentration. However, the suggested acceptable value is 0.3 mg/L. A comparison of these glyphosate concentrations indicates that an overspray with Roundup may cause unacceptable mortality in shallow water bodies.

CONCLUSIONS

In this investigation off-target deposit from various aerial applications of glyphosate (Roundup) was measured, and estimates were made of the buffer widths required around water to protect salmon, rainbow trout and various aquatic invertebrates from significant direct toxicological effects. In general the least and greatest off-target deposits resulted from the MICRO-

FOIL and D8-46 applications respectively. Model calculations for a 100 ha (1 x 1 km) glyphosate application, based on experimental data, indicate that glyphosate deposits on water surfaces fall to 1% of the maximum recommended a.i. application rate (2.1 kg a.e./ha) at downwind distances from the final swath of less than 25m for the MICROFOIL and TVB applications and about 49m for the D8-46 application. For the MICROFOIL and TVB use strategies tried, a buffer width of 25m from the final downwind swath will limit predicted Roundup concentrations to less than 1 mg/L in water depths greater than 10cm. For the D8-46 hydraulic nozzle application tested a 30 m buffer is needed to prevent swath displacement in high windspeeds causing concentrations in excess of this level.

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